Higgs Boson Phenomenology in the Type II Two Higgs Doublet Model (2HDM)

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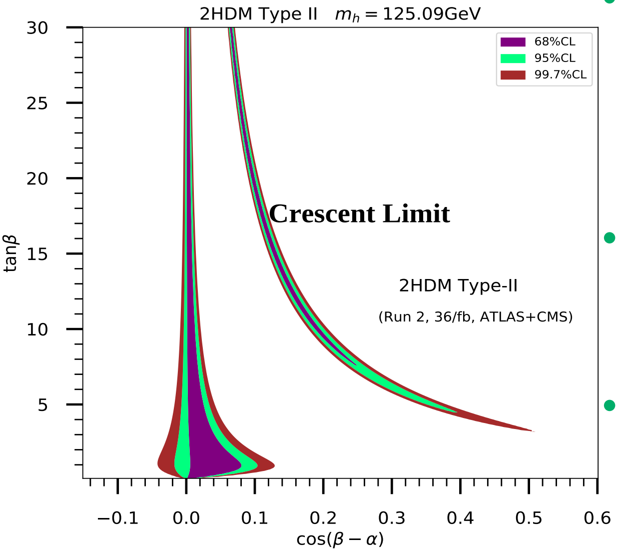
Outline

Overview of our Work
Two Higgs Doublet Model (2HDM)
Constraints on $\cos(\beta - \alpha)$ and $\tan\beta$ in the 2HDM Type II
Results and Discussion
Heavy Higgs (H) Bosons in the 2HDM
CP Odd Higgs (A) Bosons in the 2HDM
Charged Higgs $(H^{\pm})$ Bosons in the 2HDM
Summary and Conclusion

Outline

Overview of our Work



- We present a strategy to study the parameter space of the Type − II CP conserving Two Higgs Doublet Model with a softly broken Z_2 symmetry by parametrizing the Higgs scalar potential in the physical basis.
- We also impose certain theoretical constraints on the masses of H, A, and $H^{\pm}$ to eliminate all exotic decays, and to allow space for SM particle decays.
- Our results suggest that in the crescent limit, when kinematically accessible $H \to hh$, $A \to Zh$ and $H^{\pm} \to W^{\pm}h$ should become high priorities in searching for additional Higgs bosons.

Outline

The Model

1. Simplest extended Higgs model.
2. SM: Φ_1 2HDM: Φ_1, Φ_2
3. Physical states h $h, H, A, H^\pm$

2HDM {
- MSSM, NMSSM, etc
- Neutrino mass model

1. Hence, it will be valuable to study collider phenomenology of 2HDM.

Two Higgs Doublet Model (2HDM)

Field Content and Symmetries

Two scalar $SU(2)$ doublets : Φ_1 and Φ_2

$$\mathcal{L}_S = \sum_{i=1}^{2} (D_\mu \Phi_i)^\dagger (D^\mu \Phi_i) - V_{\text{2HDM}} \ , \qquad D_\mu = \partial_\mu - \frac{i}{2} g \sum_{a=1}^{3} \sigma^a W_\mu^a - \frac{i}{2} g' B_\mu$$

1. The most general Higgs potential is given by:

$$\begin{aligned} V_{\text{2HDM}} = {} & m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - (m_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) \\ & + \frac{1}{2}\lambda_1 |\Phi_1|^4 + \frac{1}{2}\lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 \\ & + \frac{1}{2}[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 |\Phi_1|^2 \Phi_1^\dagger \Phi_2 + \lambda_7 |\Phi_2|^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}], \end{aligned} \tag{1}$$

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1. And the scalar potential of a CP-conserving with a softly broken Z_2 symmetry $(\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2)$:

$$\begin{aligned} V_{\text{2HDM}} = {} & m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - (m_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) \\ & + \frac{1}{2}\lambda_1 |\Phi_1|^4 + \frac{1}{2}\lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 \\ & + \frac{1}{2}\left[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \cancelto{0}{\lambda_6 |\Phi_1|^2 \Phi_1^\dagger \Phi_2} + \cancelto{0}{\lambda_7 |\Phi_2|^2 \Phi_1^\dagger \Phi_2} + \text{h.c.}\right], \end{aligned} \tag{2}$$

Higgs scalar potential in different bases

- 4 different bases:

1. General basis
   $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \tan\beta$
2. Physical basis
   $m_h, m_H, m_A, m_{H^\pm}, \sin(\beta-\alpha), m_{12}^2, \tan\beta$
3. Higgs Hunter's Guide basis
4. Higgs basis

Two Higgs Doublet Model (2HDM)

Physical Basis

- After EWSB;

1. 4 Scalar physical states: $m_h, m_H, m_A, m_{H^\pm}$
2. the ratio of the Higgs vacuum expectation values $\tan\beta \equiv \frac{v_2}{v_1}$ where, $v_1^2 + v_2^2 = v^2\,(v = 246\text{GeV})$
3. two mixing angles, α and β

$$\lambda_1 = \frac{1}{v^2\cos^2\beta}\left[-\sin^2\beta M^2 + \cos^2\alpha m_H^2 + \sin^2\alpha m_h^2\right],$$

$$\lambda_2 = \frac{1}{v^2\sin^2\beta}\left[-\cos^2\beta M^2 + \sin^2\alpha m_H^2 + \cos^2\alpha m_h^2\right],$$

$$\lambda_3 = -\frac{M^2}{v^2} + \frac{2m_{H^\pm}^2}{v^2} + \frac{1}{v^2}\frac{\sin 2\alpha}{\sin 2\beta}(m_H^2 - m_h^2),$$

$$\lambda_4 = \frac{1}{v^2}(M^2 + m_A^2 - 2m_{H^\pm}^2), \qquad \lambda_5 = \frac{1}{v^2}(M^2 - m_A^2).$$

Classes of Two Higgs Doublet Model

Table 1: Yukawa couplings for the Four classes of 2HDM

	Type-I	Type-II	ℓ-specific (Type-X)	Flipped (Type-Y)
Up-type	Φ_2	Φ_2	Φ_2	Φ_2
Down-type	Φ_2	Φ_1	Φ_2	Φ_1
Leptons	Φ_2	Φ_1	Φ_1	Φ_2

The type II model is of particular interest because the Higgs sector of the **MSSM** is a 2HDM of type II.

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Theoretical and experimental constraints

Theoretical constraints

- Vacuum stability
- Tree level unitarity
- Perturbativity of the potential

Experimental constraints

- signal strength measurements of the SM Higgs

$$\mu_j^X = \frac{[\sigma_j(h) \times Br(h \to X)]^{\text{2HDM}}}{[\sigma_j(h) \times Br(h \to X)]^{\text{SM}}} \quad (3)$$

- The heavy neutral Higgs searches.

$$m_H = m_{H^\pm} + 50\text{GeV}; \qquad m_H = m_A + 50\text{GeV} \quad (4)$$

Parameter space and constraints

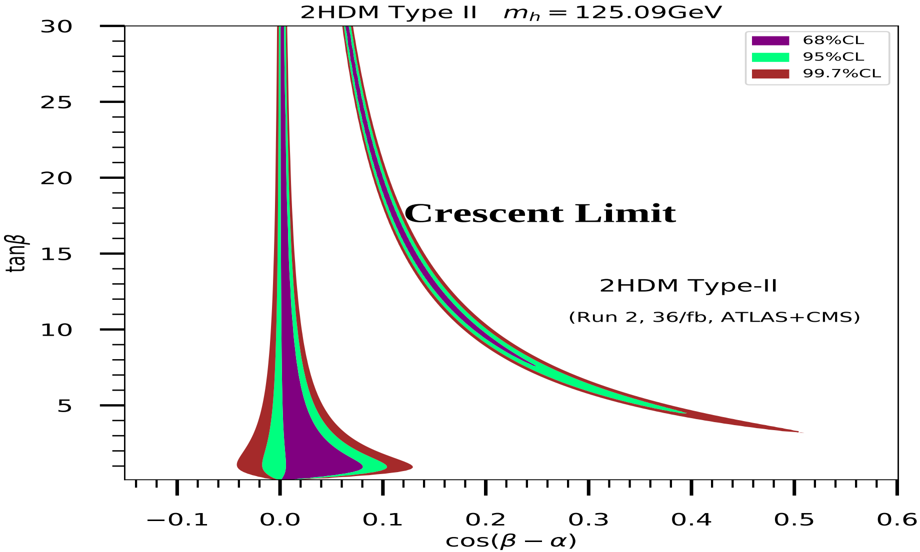


Figure 1: Constraints on $\cos(\beta-\alpha)$ and $\tan\beta$ in the 2HDM Type II

Limiting Cases

1. Decoupling limit

- For $m_{12}^2 \gg v^2$, h becomes SM like, $\cos(\beta-\alpha)=0$ and the other bosons are heavy.

2. Near Decoupling limit

- For $m_{12}^2 \gg v^2$, h is not exactly SM like, $\cos(\beta-\alpha)=0.04$ and the other bosons are heavy.

3. Crescent limit

- At relatively large values of $\cos(\beta-\alpha)$ and the other bosons are heavy.

Benchmark scenarios

Table 2: Benchmark points for heavy Higgs searches in the decoupling limit

Scenario A (Decoupling limit)				
	m_h (GeV)	m_H (TeV)	$c_{\beta-\alpha}$	$\tan\beta$
A.1	125	$0.2-1.5$	0.0	1
A.2	125	$0.2-1.5$	0.0	7.8
A.3	125	$0.2-1.5$	0.0	15
A.4	125	$0.2-1.5$	0.0	20

Table 3: Benchmark points for heavy Higgs searches near the decoupling limit

Scenario B (Near the decoupling limit)				
	m_h (GeV)	m_H (TeV)	$c_{\beta-\alpha}$	$\tan\beta$
B.1	125	$0.2-1.5$	0.004	1
B.2	125	$0.2-1.5$	0.004	7.8
B.3	125	$0.2-1.5$	0.004	15
B.4	125	$0.2-1.5$	0.004	20

Benchmark scenarios

Table 4: Benchmark points for heavy Higgs searches in the crescent limit

Scenario C (Crescent limit)				
	m_h (GeV)	m_H (TeV)	$c_{\beta-\alpha}$	$\tan\beta$
C.1	125	$0.2 - 1.5$	0.35	5
C.2	125	$0.2 - 1.5$	0.24	7.8
C.3	125	$0.2 - 1.5$	0.13	15
C.4	125	$0.2 - 1.5$	0.1	20

Outline

Heavy Higgs (H) Bosons in the 2HDM

$$\sigma_{\text{NLO}}(gg \to H)\Big|_{\alpha,\beta} = \sigma_{\text{NLO}}(gg \to h_{\text{sm}}) \frac{\Gamma_{\text{LO}}(H \to gg)\Big|_{\alpha,\beta}}{\Gamma_{\text{LO}}(h_{\text{sm}} \to gg)} \tag{5}$$

Table 5: The Yukawa factors in the Type II - 2HDM for heavy Higgs

H couplings $\frac{y_{2HDM}}{y_{SM}}$	2HDM Type II
C_V^H	$\cos(\beta-\alpha)$
C_u^H	$\cos(\beta-\alpha) - \frac{\sin(\beta-\alpha)}{\tan\beta}$
C_d^H	$\cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)$
C_l^H	$\cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)$

$$g_{Hhh} = \frac{\cos(\beta-\alpha)}{v}\left\{\left(\frac{6m_{12}^2}{\sin 2\beta} - m_H^2 - 2m_h^2\right)\left(\cos 2(\beta-\alpha) - \frac{\sin 2(\beta-\alpha)}{\tan 2\beta}\right) - \frac{2m_{12}^2}{\sin 2\beta}\right\}, \tag{6}$$

Heavy Higgs (H) Bosons in the 2HDM

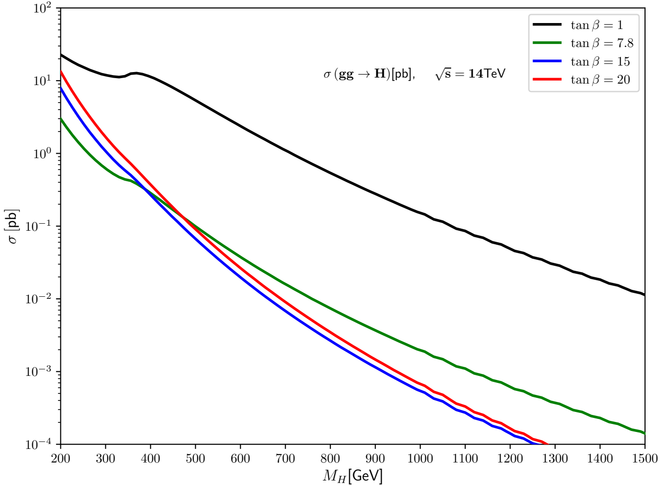
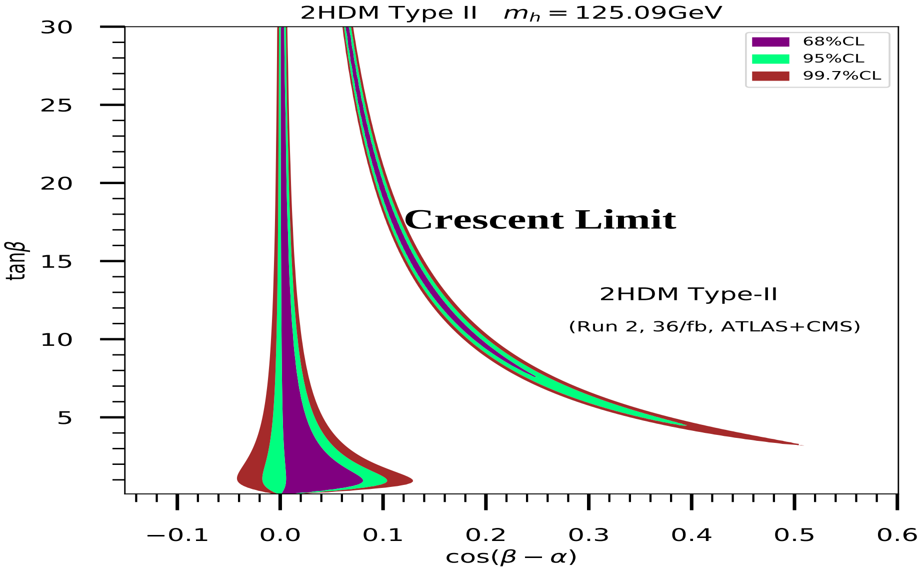


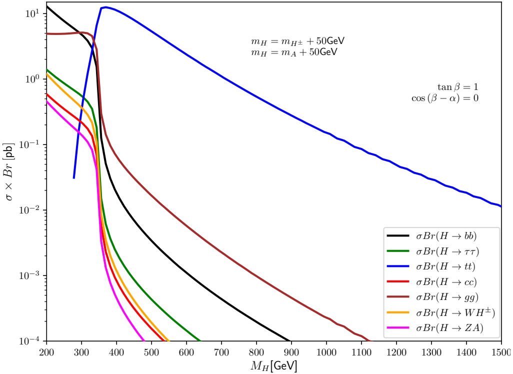
Figure 2: σ_{ggH} in the decoupling limit for $\tan\beta = 1, 7.8, 15$ and 20 at NLO

Parameter space and constraints



Scenario A (Decoupling limit): Heavy Higgs searches

σ_{ggH} times branching ratios vrs m_H in the decoupling limit at $\cos(\beta-\alpha)=0$



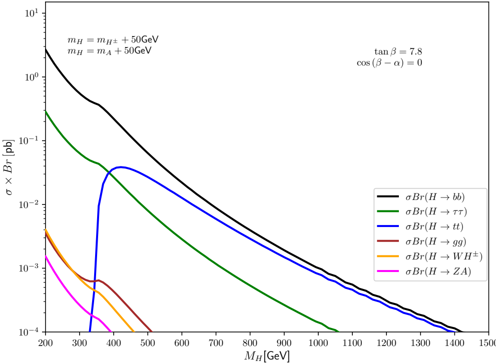


Figure 3: σ_{ggH} times branching ratios vrs m_H for $\tan\beta = 1$ (left), and $\tan\beta = 7.8$ (right) at NLO

Scenario A (Decoupling limit): Heavy Higgs searches

σ_{ggH} times branching ratios vrs m_H in the decoupling limit at $\cos(\beta-\alpha)=0$

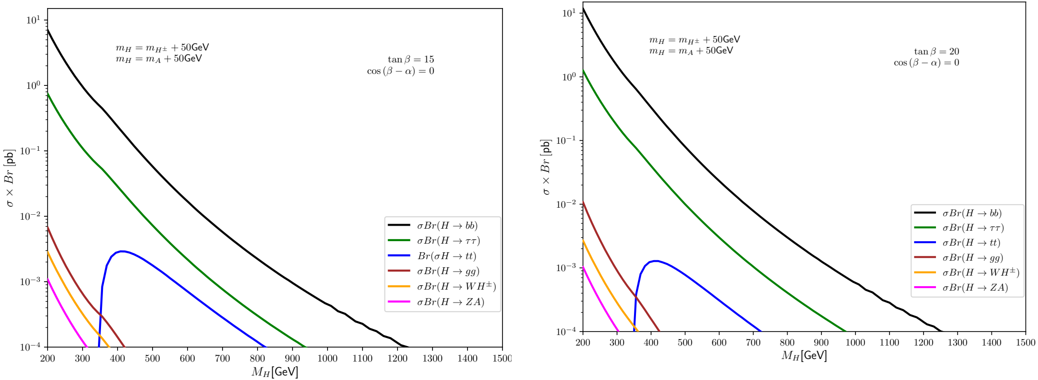
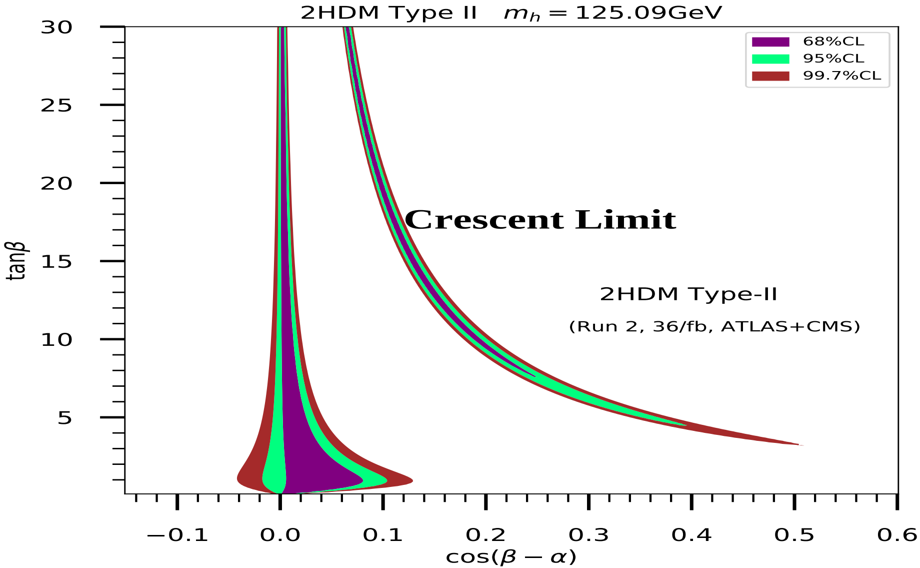


Figure 4: σ_{ggH} times branching ratios vrs m_H for $\tan\beta = 15$ (left), and $\tan\beta = 20$ (right) at NLO

Parameter space and constraints



Scenario C (Crescent limit): Heavy Higgs searches

σ_{ggH} times branching ratios vrs m_H in the crescent limit at $\cos(\beta-\alpha)=0.35$(left) and $cos(\beta-\alpha)=0.24$(right)

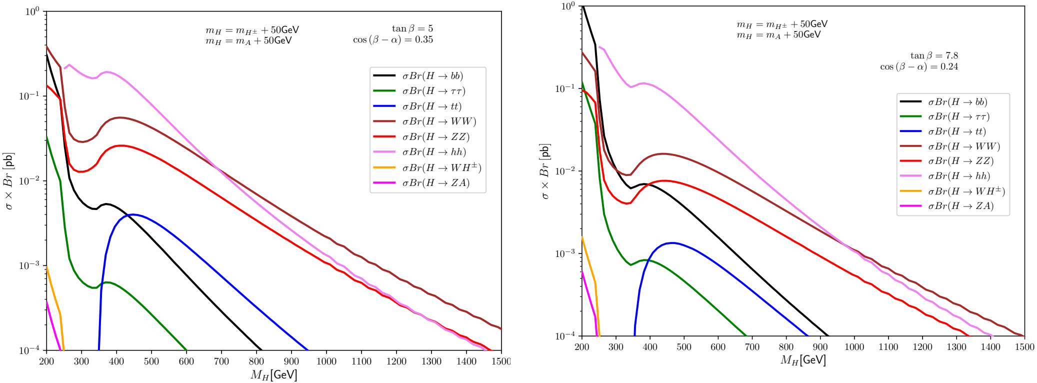


Figure 5: σ_{ggH} times branching ratios vrs m_H for $\tan\beta=5$ (left), and $\tan\beta=7.8$ (right) at NLO

Scenario C (Crescent limit): Heavy Higgs searches

σ_{ggH} times branching ratios vrs m_H in the crescent limit at $\cos(\beta-\alpha)=0.13$(left) and $cos(\beta-\alpha)=0.1$(right)

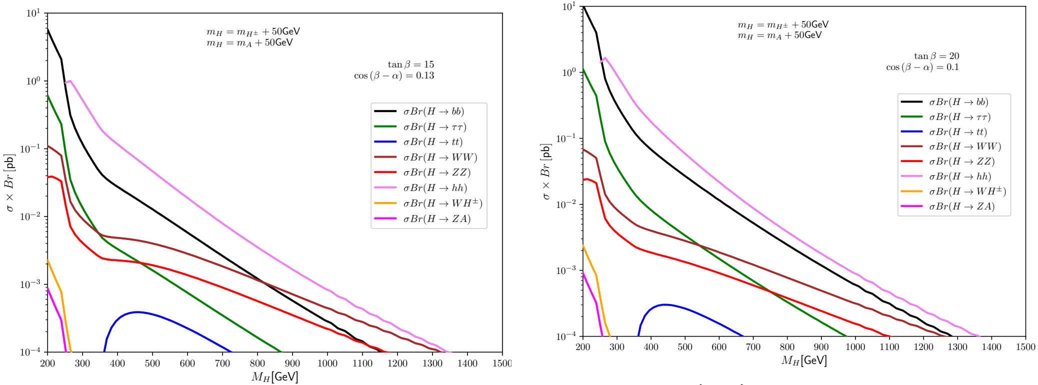


Figure 6: σ_{ggH} times branching ratios vrs m_H for $\tan\beta = 15$ (left), and $\tan\beta = 20$ (right) at NLO

Summary: Heavy Higgs searches

1. We found that the dominant cross section rates contribution comes from the top quark loops as the $g_{t\bar{t}}$ couplings, $g_{Htt} \propto \frac{1}{\tan\beta}$ are so strong.
2. We also found that in the decoupling limit, certain decay channels such as $H \to WW$ and $H \to ZZ$ vanish.
3. Interestingly, $H \to hh$, $H \to WW$ and $H \to ZZ$ become promising final states in the crescent limit.

CP Odd Higgs (A) Bosons in the 2HDM

$$\sigma_{\text{NLO}}(gg \to A)\Big|_{\alpha,\beta} = \sigma_{\text{NLO}}(gg \to h_{\text{sm}}) \frac{\Gamma_{\text{LO}}(A \to gg)\Big|_{\alpha,\beta}}{\Gamma_{\text{LO}}(h_{\text{sm}} \to gg)} \tag{7}$$

Table 6: Yukawa interactions of A.

CP-odd Higgs A couplings $\frac{y_{2HDM}}{y_{SM}}$	2HDM Type II
C_V^A	0
C_u^A	$\frac{1}{\tan\beta}$
C_d^A	$\tan\beta$
C_l^A	$\tan\beta$

The couplings of two scalars, h, and A to an SM vector boson Z can be written in terms of α and β as;

$$g_{hZA} = \frac{1}{2}\sqrt{g^2 + g'^2}\cos(\beta - \alpha) \tag{8}$$

CP Odd Higgs (A) Bosons in the 2HDM

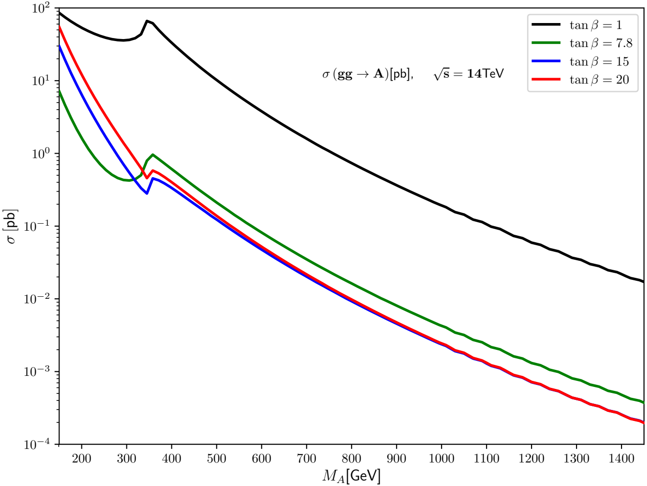
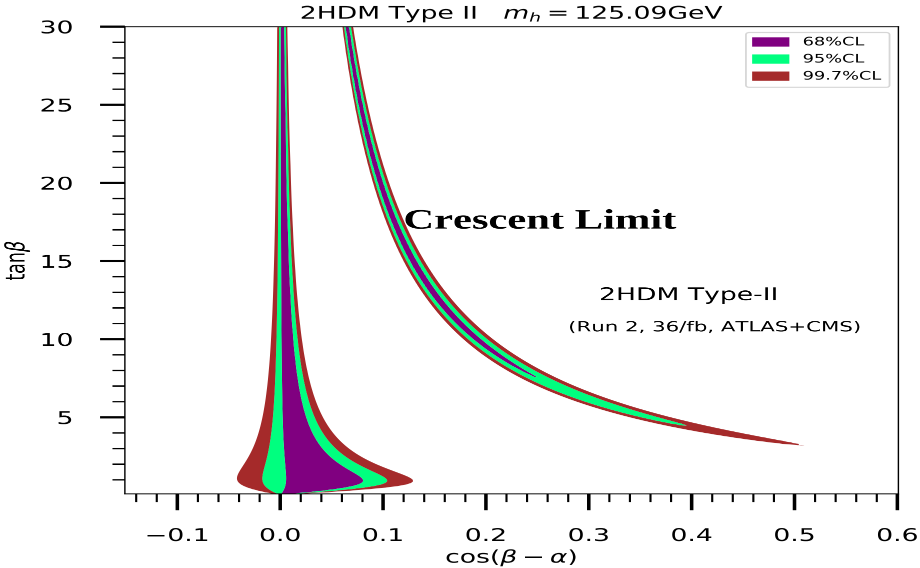


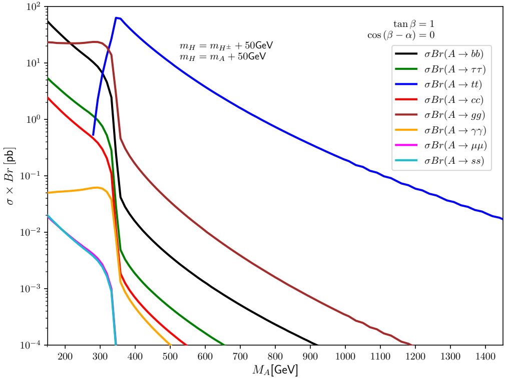
Figure 7: σ_{ggA} in the decoupling limit for $\tan\beta = 1, 7.8, 15$ and 20 at NLO

Parameter space and constraints



Scenario A (Decoupling limit): CP Odd Higgs searches

σ_{ggA} times branching ratios vrs m_A in the decoupling limit at $\cos(\beta-\alpha)=0$



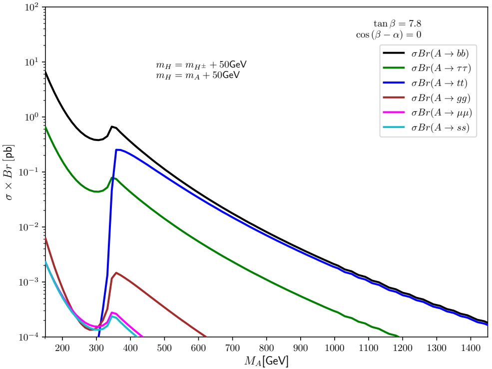


Figure 8: σ_{ggA} times branching ratios vrs m_A for $\tan\beta = 1$ (left), and $\tan\beta = 7.8$ (right) at NLO

Scenario A (Decoupling limit): CP Odd Higgs searches

σ_{ggA} times branching ratios vrs m_A in the decoupling limit at $\cos(\beta-\alpha)=0$

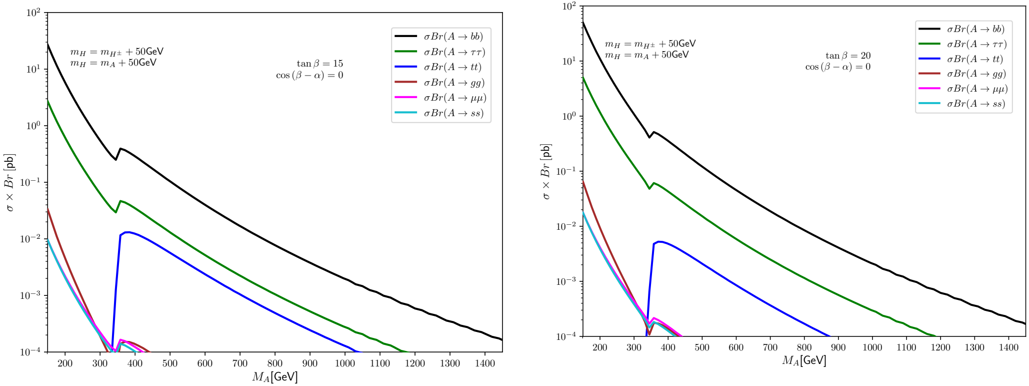
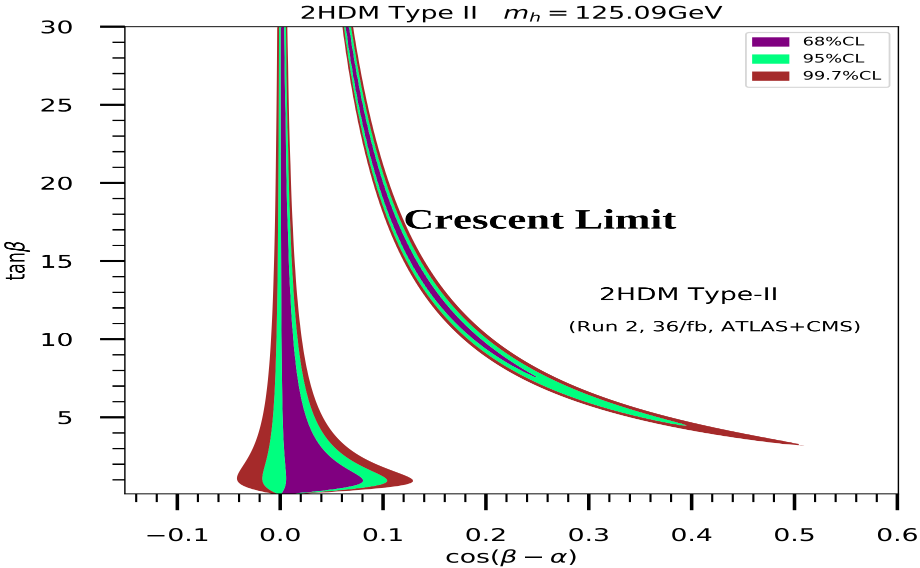


Figure 9: σ_{ggA} times branching ratios vrs m_A for $\tan\beta = 15$ (left), and $\tan\beta = 20$ (right) at NLO

Parameter space and constraints



Scenario C (Crescent limit): CP Odd Higgs searches

σ_{ggA} times branching ratios vrs m_A in the crescent limit at $\cos(\beta-\alpha)=0.35$(left) and $cos(\beta-\alpha)=0.24$(right)

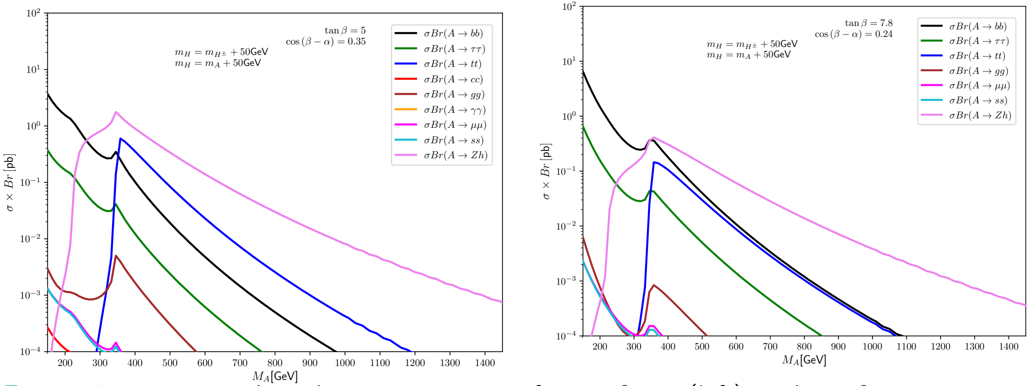


Figure 10: σ_{ggA} times branching ratios vrs m_A for $\tan\beta = 5$ (left), and $\tan\beta = 7.8$ (right) at NLO

Scenario C (Crescent limit): CP Odd Higgs searches

σ_{ggA} times branching ratios vrs m_A in the crescent limit at $\cos(\beta-\alpha)=0.13$(left) and $cos(\beta-\alpha)=0.1$(right)

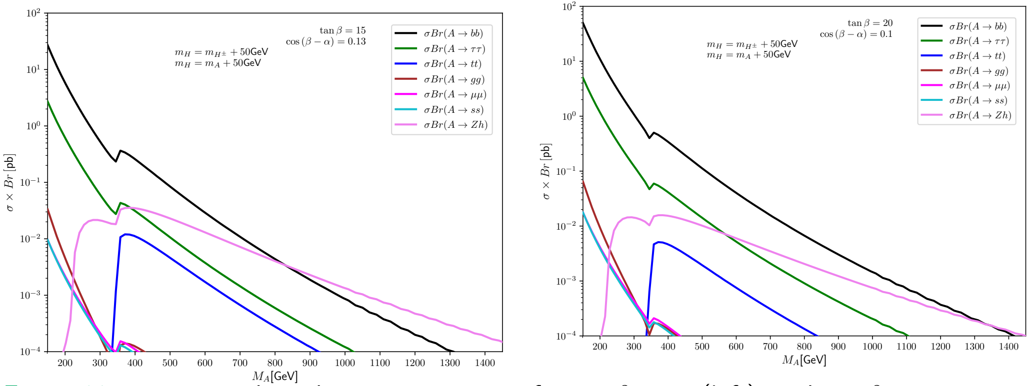


Figure 11: σ_{ggA} times branching ratios vrs m_A for $\tan\beta = 15$ (left), and $\tan\beta = 20$ (right) at NLO

Summary: CP Odd Higgs searches

1. We observed that in the low $\tan\beta$ regime, larger cross sections rates are from the top quark loops as the g_{Att} couplings, $g_{Att} \propto \frac{1}{\tan\beta}$ are so strong.

2. In the high $\tan\beta$ regime, the coupling of A to the top quark loop g_{Att} are strongly suppressed while those to the bottom quarks g_{Abb} are enhanced.

3. We found that the dominant decay modes for A are $A \to b\bar{b}$, $A \to gg$, $A \to \tau^+\tau^-$, $A \to Zh$ and $A \to t\bar{t}$. The $A \to Zh$ is dominant in the crescent limit in the low $\tan\beta$ regime.

Charged Higgs $(H^{\pm})$ Bosons in the 2HDM

1. Fermionic channel, $gg \to H^+ b\bar{t}$
2. Fermionic channel, $g\bar{b} \to H^+ \bar{t}$
3. Bosonic channel, $gg \to H_j \to H^+ W^-$

$$\sigma_{H^{\pm}}^{\text{Type II}} \propto g_t^2 \sigma_t \cot^2\beta + g_b \sigma_b \tan^2\beta + g_t g_b \sigma_{tb} \quad (9)$$

Table 7: Mixing factors in Yukawa interactions of $H^{\pm}$

Charged Higgs $H^{\pm}$ couplings $\frac{y_{2HDM}}{y_{SM}}$	2HDM Type II
$C_V^{H^{\pm}}$	0
$C_u^{H^{\pm}}$	$\cot\beta$
$C_d^{H^{\pm}}$	$-\tan\beta$
$C_l^{H^{\pm}}$	$-\tan\beta$

$$g_{hW^{\pm}H^{\pm}} = \mp\frac{i}{2} g \cos(\beta-\alpha) \quad (10)$$

Charged Higgs $(H^{\pm})$ Bosons in the 2HDM

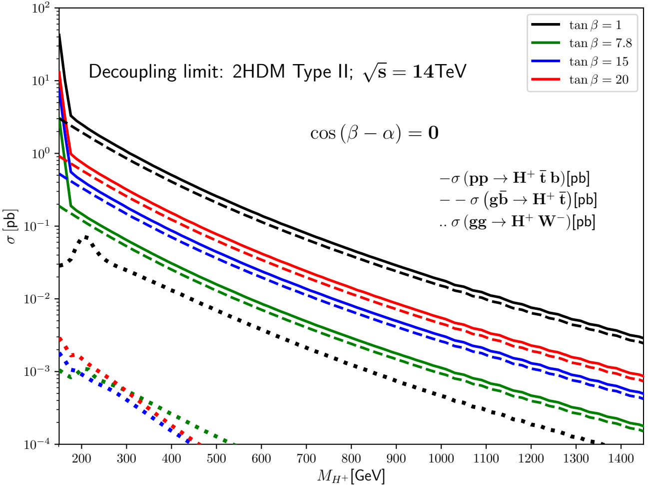
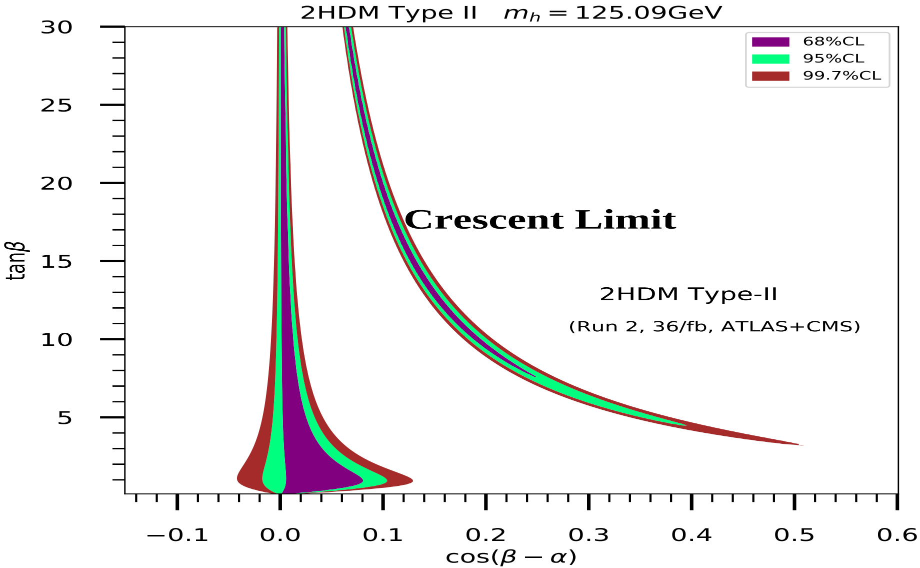


Figure 12: Cross section rates for charged Higgs in the decoupling limit

Parameter space and constraints



Scenario A (Decoupling limit): $H^{\pm}$ Higgs searches

$\sigma\,(pp \to H^{+}\,\bar{t}\,b)$ times branching ratios vrs $m_{H^{\pm}}$ in the decoupling limit at $\cos(\beta-\alpha)=0$

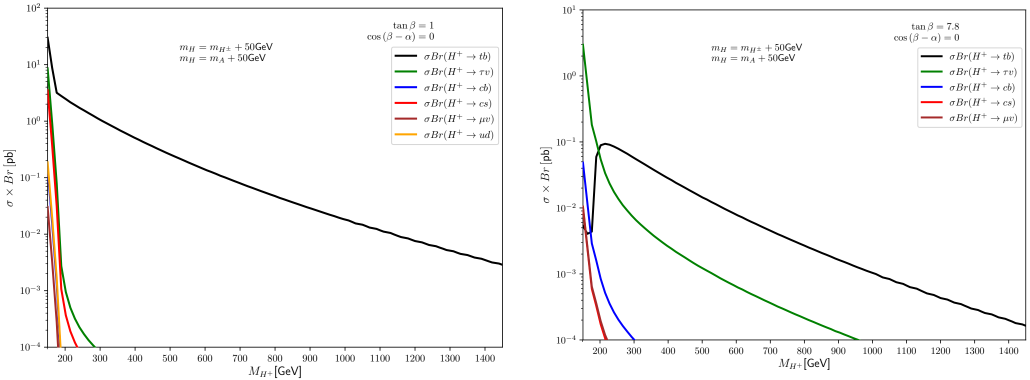


Figure 13: $\sigma\,(pp \to H^{+}\,\bar{t}\,b)$ times branching ratios vrs $m_{H^{\pm}}$ for $\tan\beta = 1$ (left), and $\tan\beta = 7.8$ (right) at NLO

Scenario A (Decoupling limit): $H^{\pm}$ Higgs searches

$\sigma\left(pp \to H^{+}\,\bar{t}\,b\right)$ times branching ratios vrs $m_{H^{\pm}}$ in the decoupling limit at $\cos(\beta-\alpha)=0$

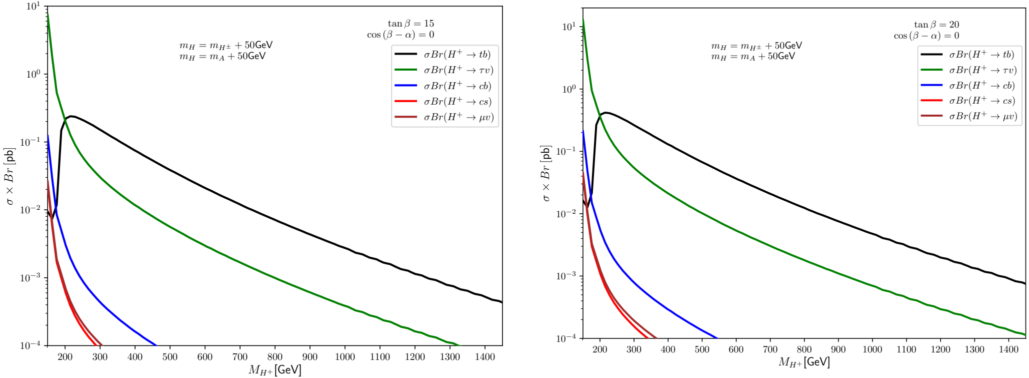
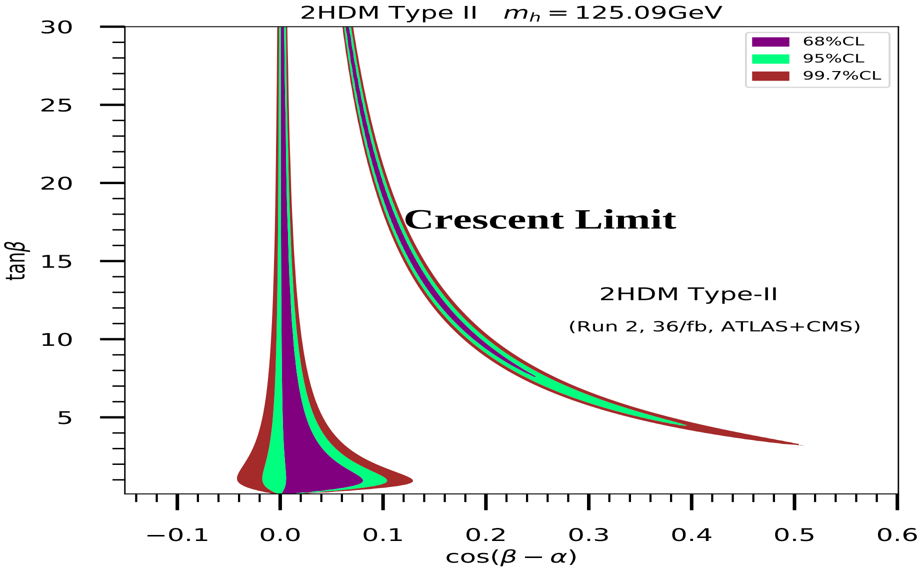


Figure 14: $\sigma\left(pp \to H^{+}\,\bar{t}\,b\right)$ times branching ratios vrs $m_{H^{\pm}}$ for $\tan\beta = 15$ (left), and $\tan\beta = 20$ (right) at NLO

Parameter space and constraints



Scenario C (Crescent limit): $H^{\pm}$ Higgs searches

$\sigma\left(pp \rightarrow H^{+}\,\bar{t}\,b\right)$ times branching ratios vrs $m_{H^{\pm}}$ in the crescent limit at $\cos(\beta-\alpha)=0.35$(left) and $cos(\beta-\alpha)=0.24$(right)

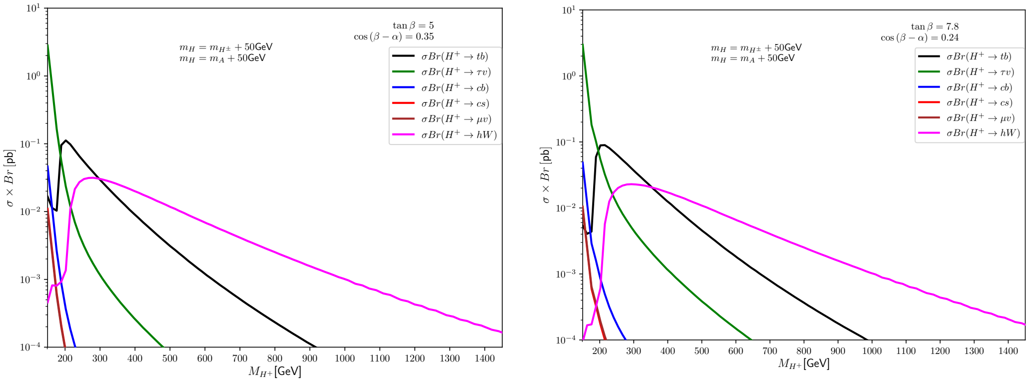
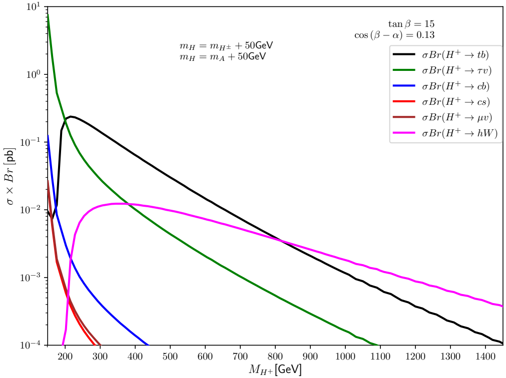


Figure 15: $\sigma\left(pp \rightarrow H^{+}\,\bar{t}\,b\right)$ times branching ratios vrs $m_{H^{\pm}}$ for $\tan\beta = 5$ (left), and $\tan\beta = 7.8$ (right) at NLO

Scenario C (Crescent limit): $H^\pm$ Higgs searches

$\sigma\left(pp \to H^+\,\bar{t}\,b\right)$ times branching ratios vrs $m_{H^\pm}$ in the crescent limit at $\cos(\beta-\alpha) = 0.13$(left) and $cos(\beta-\alpha) = 0.1$(right)



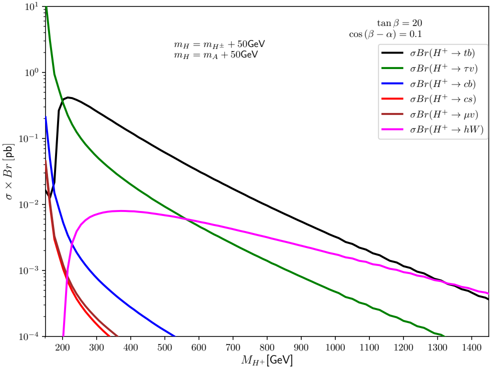


Figure 16: $\sigma\left(pp \to H^+\,\bar{t}\,b\right)$ times branching ratios vrs $m_{H^\pm}$ for $\tan\beta = 15$ (left), and $\tan\beta = 20$ (right) at NLO

Summary: $H^{\pm}$ Higgs searches

1. For the charged Higgs bosons, the most dominant production channel was found to be the $pp \to H^{+}\bar{t}b$ state.

2. Our results also showed that the dominant decay mode for the charged Higgs in type II 2HDM model, as expected is in the $\bar{t}b$ channel, following the sub-dominant ones $\bar{\tau}\nu_{\tau}$ channel with Br $\sim 10-15$ %, followed by other suppressed modes such as, $H^{+} \to \bar{b}c, c\bar{s}, \mu\nu_{\mu}$ and a new channel $H^{\pm} \to hW^{\pm}$ opens up for larger values of $\cos(\beta-\alpha)$.

Outline

Summary and Conclusion

1. The crescent limit allows us to probe non-SM Higgs phenomenology that is of interest for future LHC Higgs searches.
2. Our results suggest that $H \to hh$, $A \to Zh$ and $H^{\pm} \to W^{\pm}h$ should become high priorities in searching for additional Higgs bosons.

Outlook

- CP Violating 2HDM
- WEDM, a BSM scenario which allows excitations of the SM particles to propagate in an extra dimension.

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THANK YOU